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Study on the Deformation of 3%Si-Fe Single Crystal with Magnetic Field Being Deviated from [001]

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Abstract — We have investigated the magnetostriction and the magnetization process of 3%Si-Fe single crystal with (110) parallel to the surface, when the direction of magnetization is deviated from [001]. It was found that large contraction and expansion occurred as a result of magnetostriction in the magnetization process, even if the deviation angle was small. Complicated magnetic domain structures were observed with external field being applied. The behavior of magnetostriction corresponds to changes of magnetic domain structure. On the basis of the principle that no magnetic pole appears at domain walls, a model of domain structure is proposed. Using the model, the deformation behavior was explained well.

I. Introduction

Recently, an acoustic noise of power transformers has become a large environmental problem. The magnetization process of grain-oriented silicon steel is parallel displacement of 180 degree domain wall, therefore no magnetostriction occurred to the longitudinal direction. However the noise is thought to be produced at the corners of laminated core of transformers because the magnetization is deviated from [001] of the grain-oriented silicon steel core at the corners. When the direction of the magnetization is not parallel to the [001], a large deformation will be induced by magnetostriction with rotation of magnetization. In addition, not only acoustic noise but also large electric power losses occur with magnetostriction. However, the mechanism of magnetostriction behavior with the magnetization process couldn't be explained synthetically by previous works [1]-[6]. Therefore we investigated the magnetization process and the domain structure of 3%Si-Fe single crystal with magnetic field being deviated from [001].

This paper reports about the deformation by magnetostriction in magnetization processes about (110) 3%Si-Fe single crystal when the magnetization is deviated from [001] axis. In addition, the mechanism of the deformation by magnetostriction is discussed.

II. Experimental procedure

The sample used in this study was 230 μm thick 3%Si-Fe single crystal with (110) parallel to the surface. As shown in Fig. 1, samples were cut out at various [001] deviation angles to longitudinal direction, length of 60 mm and width of 4 mm. After cutting out, samples were pickled and annealed in a vacuum of 1×10^{-3} Pa in order to make a smooth surface.

Magnetostriction was measured by an equipment using three-terminal-capacitance method [7]. Fig. 2 shows schematic diagram of the measuring equipment for magnetostriction. One end of sample is fixed and the other end is attached to a movable electrode of capacitance cell through a copper wire. In order to avoid magnetic influence on the sample, the equipment was made in brazen. By the expansion and contraction of the sample, the movable electrode was moved, therefore the capacitance between the movable and fixed electrodes change. The amount of these changes were measured by a balanced circuit which were composed of three-terminal-capacitance bridge and lock-in amplifier. In this study, the direction of applied magnetic field and measuring direction of the magnetization and magnetostriction were parallel to the longitudinal direction of the samples.

The magnetization curves were measured by DC B-H loop tracer.

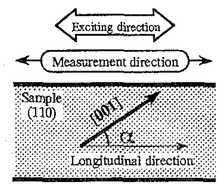

Fig. 1 Sample with the relation between longitudinal direciton and [001] axis.

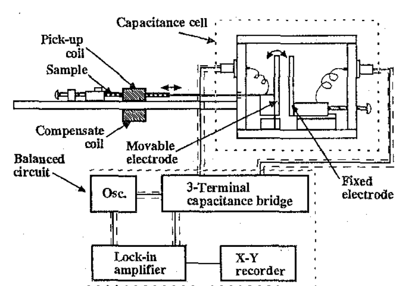

Fig. 2 Schematic diagram of the measurement system.

The change of domain structure with magnetization process was observed using scanning electron microscopy by means of Lorentz micrography (type-II) [8]-[10].

III. Results and discussion

Fig. 3 shows the magnetization curves measured with the samples having various deviation angles between [001] and

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exciting direction. In these curves, there are two bends which are the changing points of inclination. The curves are separated into three partitions by the two bends which are called primary and secondary bends in this paper.

The magnetization and magnetostriction curves were measured in varying field. As an example the measured curve on the deviation angle of 10 degree is shown in Fig. 4. A large contraction and expansion were observed in magnetostriction curve. The changing points from contraction to expansion which are indicated by broken line in Fig. 4 correspond to the secondary bend of magnetization curve. The behaviors of magnetostriction were changed variously with deviation angle α. However, the inclination of all the magnetostriction curves changed at the secondary bend of the magnetization curves. Therefore, the secondary bend seems to be an important point in the magnetization process. In addition, these curve shows the sample vibrates 4 times in one period of exiting field. This means it vibration 200 Hz by exiting frequency of 50 Hz. The points of appearance of 4th harmonic acoustic noise of transformers are thought to be the corners of transformers, because there are some deviation angles between [001] and flux direction at the corners.

According to the results of the magnetization curves and magnetostriction measurements, the magnetization process of the samples with deviation angle from [001] can not be explained by the displacement of 180 degree domain wall and the rotation of the magnetization. Therefore domain structures at the various point of the magnetization process were observed. Fig. 5 shows the domain structure of deviation angle of 10 degree. At first, a parallel displacement of 180 degree domain wall was observed less than the field of primary bend. Applying larger field, domains with diagonal walls to [001] formed from edge of the sample as shown in Fig. 5(b). At the point of secondary bend, shown in Fig. 5(c), the diagonal wall was formed in all the surface. Though the wall is not parallel to [001] in this state, the magnetization of the domains was found to be parallel to [001]. More than the field of secondary bend, parallel displacement of diagonal wall was observed as shown in Fig. 5(d). These changes of domain structure were confirmed by other deviation angle's samples. Therefore, the domain structure inside of the sample must be complex as to minimize the magnetostatic energy and magnetic anisotropy energy.

To explain the results described above, we supposed that displacement of the 90 degree domain wall occurred between primary and secondary bend. In consideration of experimental

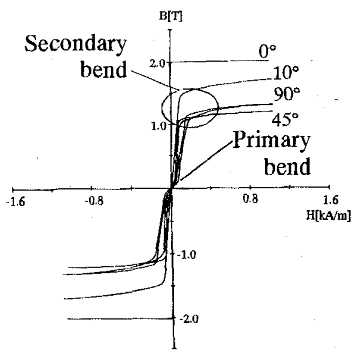


Fig. 3 Magnetization curves with deviation angle α to longitudinal direction.

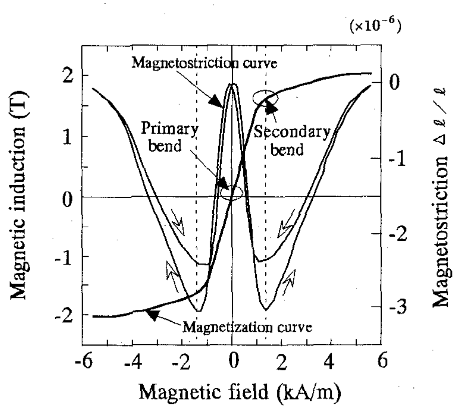
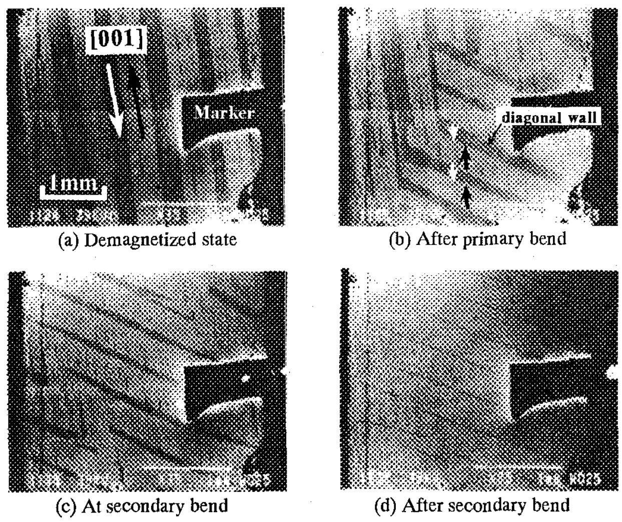


Fig. 4 Magnetization and magnetostriction curve (deviation angle α: 10 degree).



(a) Demagnetized state (b) After primary bend

(c) At secondary bend (d) After secondary bend

Fig. 5 Changes of the magnetic domain structure (deviation angle: 10 degree).

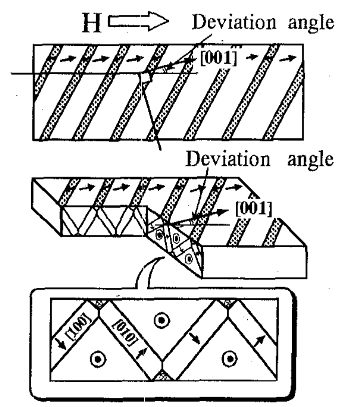


Fig. 6 Proposed model of the domain structure with the state of secondary bend.

and calculated results, we developed the model of the domain structure shown in Fig. 6. In this model, the structure of domain is divided by 90 degree domain wall and the magnetization is distributed along the three easy axes of [100], [010] and [001]. This model also satisfies the conditions that any 90 degree domain wall has no magnetic poles and volume ratio of domains of [100], [010] and [001] agree with the induction at the secondary bend.

Using the model shown in Fig. 6, we can geometrically calculate the magnetization values at secondary bend and the deformation by magnetostriction from the demagnetized state to secondary bend. Fig. 7 shows the deviation angle α dependence of the magnetic induction at the appearance point of the secondary bend. There is good agreement between the calculated and measured values. Fig. 8 shows the deviation angle α dependence of the magnetostriction at secondary bend. The calculated and the measured values agreed well too. From the results shown in Fig. 7 and 8, the proposed domain structure model satisfies the experimental results.

We found that large deformation of $-10 \sim 17\times10^{-6}$ appeared in grain-oriented silicon steels by applying field deviated from its [001] axis, because of 90 degree domain wall displacement in smaller field than the secondary bend and the rotation magnetization in larger field. Even if the deviation angle was only 10 degree, while the saturation magnetostriction was very small, deformation at the secondary bend was as large as 3×10^{-6} shown in Fig. 4 and 8.

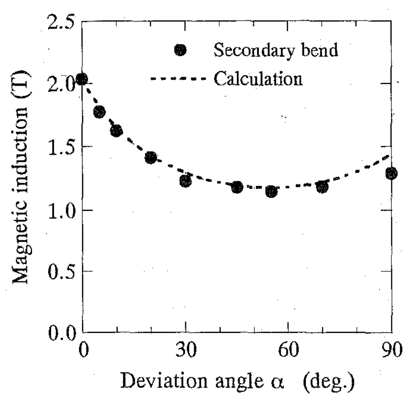


Fig. 7 Comparison of the calculated and measured magnetic induction values at appearance point of secondary bend.

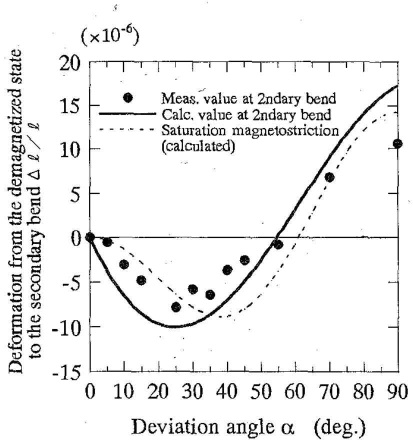


Fig. 8 Comparison of the calculated and measured magnetostriction from the demagnetized state to the secondary bend.

IV. Conclusion

In order to clarify the mechanism of occurrence of power transformer's acoustic noise, we studied the magnetization process, magnetostriction and the domain structure of 3%Si-Fe (110) single crystal with deviation angle from [001] axis to longitudinal direction. The results are summarized as follows.

(1) The magnetization process is divided into three partitions. It began with a parallel displacement of 180 degree domain wall. With increasing field, domains with diagonal wall to [001] grew from the edge of the sample. After the completion of the diagonal domain structure, rotation of the magnetization occurred.

(2) Large magnetostriction was observed in small exciting field between primary and secondary bend. The displacement of 90 degree domain wall makes large magnetostriction in this partition.

(3) The proposed domain structure model can explain the large deformation by the magnetostriction of the sample.

Acknowledgment

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